November 2003 • NREL/CP-500-34837

Conference Paper

The Effect of Load Phase Angle on Wind Turbine Blade Fatigue Damage

Preprint

D.L. White and W.D. Musial

To be presented at the 42nd AIAA Aerospace Sciences Meeting and Exhibit
Reno, Nevada
January 5–8, 2004

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle

Contract No. DE-AC36-99-GO10337

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

THE EFFECT OF LOAD PHASE ANGLE ON WIND TURBINE BLADE FATIGUE DAMAGE[1]

Darris White and Walt Musial
National Renewable Energy Laboratory
Golden, CO 80401
Darris_White@nrel.gov
Walter_Musial@nrel.gov

ABSTRACT

This paper examines the importance of load phase angle variations with respect to fatigue damage. The operating loads on a generic three bladed up-wind 1.5-MW wind turbine blade were analyzed over a range of operating conditions, and an aggregate probability distribution for the actual phase angles between the peak in-plane (lead-lag) and peak out-of-plane (flap) loads was determined. Using a finite element model (FEM) of the 1.5-MW blade and Miner's Rule [1], the accumulated theoretical fatigue damage (based on axial strains) resulting from a fatigue test with variable phase angles using the aggregate distribution was compared to the damage resulting from a fatigue test with a constant phase angle. The FEM nodal damage distribution at specific blade cross-sections are compared for the constant and variable phase angle cases. Single-node stress concentrations were distributed arbitrarily around one cross section to simulate material defects in a blade undergoing testing. Results show that the variable phase angle case results in higher damage on the critical nodes. In addition, the probability of discovering a material defect during a test was substantially increased when variable phase loading was used.

The effect of phase angle sequence on the damage accumulation was also considered. For this analysis, the finite element results were processed using a nonlinear damage accumulation model. Results show that the sequence of phase angle can have a large effect on the fatigue damage, and multiple, shorter length, sequences produce higher damage than a single, long, time history.

INTRODUCTION

Wind turbine blade fatigue tests are conducted to verify the ability of the blade to sustain the operating load environment over a design life of 20-years or more. The actual operating load variations are inherently complex, consisting of both stochastic and deterministic sources, including multi-axis wind shear, random three-dimensional turbulence, gravity loads, gyroscopic forces, control induced vibrations, and others. To generate the full-scale test loads, in-plane (lead-lag) and out-of-plane (flap) loads are separated into independent time series, rainflow counted into range/mean histograms that are used to derive separate damage equivalent fatigue loads (DEL). The two DELs are applied to the blade simultaneously with a constant phase angle between them using sinusoidal loading [2]. In most cases this phase angle is computed by taking the mean angle between the occurrence of the peak flap and lag loads in an azimuth averaged time series. Ostensibly, this simplification obscures the time- varying phase relationship between the lead-lag and flap loads.

The flap and lead-lag bending moments experienced by blades during operation are not sinusoidal, and the location around a given blade section profile where the maximum strain is observed can vary from one rotor revolution to the next. By contrast, the location of maximum strain occurs at virtually the same blade section location for every load cycle during a typical blade fatigue test. Consequently, significant errors may be introduced into the full-scale fatigue testing of wind turbine blades when a constant phase angle is used to describe the inherently variable flap versus lead-lag load relationship.

Historically, compromises to test accuracy have often been made as a necessary concession to conform full-scale blade tests to laboratory constraints. However, the practice of using constant phase angle in testing does not appear to be rooted in laboratory deficiencies but rather in old design methods that ignored phase angle. In fact, a test system to apply variable phase angle in the laboratory could be fairly straightforward.

This purpose of this study was to determine the importance of load phase angle variations with respect to fatigue testing damage. The first step was to determine if phase angle was changing significantly during operation, and how a varying phase angle could be applied to a test. This was done using a FAST [3] dynamics model of a generic 1.5 MW wind turbine. For a full range of wind speeds and turbulence conditions, the flap and lead lag loads were analyzed to determine their phase relationship. At each wind speed a phase angle probability distribution was determined. The individual phase angle distributions at each wind speed were then weighted by a Rayleigh wind speed probability distribution function to create a single, two-dimensional aggregate phase angle distribution, independent of wind speed, and representative of operating phase angles. Note that, the purpose was to determine how phase angle varies. Therefore, the DELs resulting from these simulations were not calculated as part of this study.

Once it was established that phase angle was indeed changing significantly, the question became, how would phase angle affect the damage accumulation during a fatigue test? To answer this, a generic finite element model (FEM) of a 1.5 MW blade, developed by Global Energy Concepts (GEC), was used to generate unit strains for flap and lead-lag loading under typical two-axis test load conditions, using DEL values from previous fatigue tests conducted at NREL [4]. Linear damage analysis (Miner's Rule) was performed at three blade cross-sections (root, max chord, and 15.75-m) using both the typical constant amplitude test phase angles and the aggregate distribution derived from FAST data. This analysis was performed first for the ideal condition, where the blade is assumed to be built flawlessly (according to its design), and also for a condition where material defects were intentionally added to the blade sections, as might be encountered in real test blade situations.

If the phase angle is varied during an actual blade test, a wide combination of sequences are possible which could still achieve the correct aggregate phase angle distribution over the duration of a blade test. Miner's Rule, used in the above analysis, cannot predict these effects; hence the finite element results were processed further using the nonlinear Marco-Starkey [5] damage accumulation model.

TURBINE MODEL

To evaluate the phase relationship between the flap and lead-lag bending moments, a dynamic model of a 1.5 MW three-bladed upwind variable-speed pitch-controlled wind turbine was used to simulate the blade response to various operating conditions. The model was created in FAST (Fatigue, Aerodynamics, Structures, and Turbulence), which is an aeroelastic design code used to model horizontal axis wind turbines using a combination of flexible and rigid bodies [3]. The operating conditions (wind speed, turbulence intensity factor, etc.) were based on the IEC class Ia wind site conditions [6]. Using the FAST model, the average of the time histories of each of the three blade root bending moments in the flap and lead-lag directions were calculated.

PHASE ANGLE DERIVATION

For fatigue testing, the DELs are applied harmonically with a distinct phase angle between the flap and lead-lag load cycles. For a test to provide design verification, the specific test parameters, including phase angle, must be derived from the operating load analysis, which is not so straightforward. While operating lead-lag loading does tend to follow harmonic trends and produce clear 1-per-revolution peaks and valleys, flap loading is more stochastic. Azimuth averaging will show however, that flap loads follow deterministic trends but with a high degree of scatter corresponding to where the maximum and minimum values occur for a given revolution [7]. This scatter contributes to a continual shifting of the resultant load vector acting on the blade. Since most of fatigue damage is likely to occur at or near the maximum bending response, phase angle should be described by using the relationship between the flap and lead-lag load peaks.

For this study, the phase angle between the flap and lead-lag forces is defined as the angular change in the turbine rotor between the maximum flap bending moment and the maximum lead-lag bending moment over a single rotation, as shown by Figure 1. The authors recognize that there are at least as many ways to define the load phase angle as there are cycle counting techniques but for the purpose of this study, it has been assumed that other definitions will produce similar results.

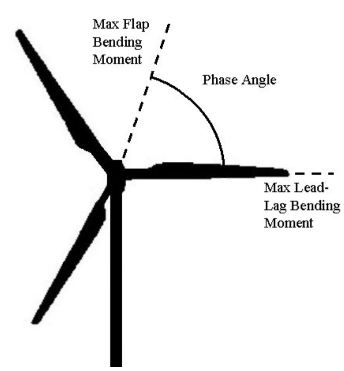

Figure 1: Phase Angle Definition

The simulated bending moments for the flap and lead-lag directions were transferred into Matlab™ and chopped into single rotor revolution length segments. The rotor angle corresponding to the maximum flap and lead-lag bending moments were calculated for each revolution, as illustrated by Figure 2.

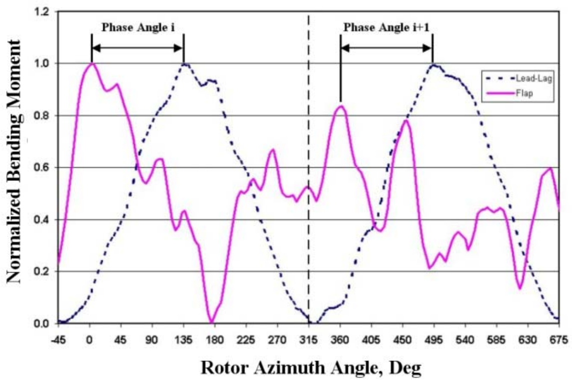

Figure 2: Example Phase Angle Calculations

For easier visualization, the bending moments have been normalized in this figure to vary from 0 to 1.

The phase angle distributions for discrete wind speeds ranging from 9 m/s to 20m/s were compiled and analyzed using 90-minute simulations. Figure 3 shows an example of one of these distributions for an average wind speed of 9 m/s. As shown the variation of the phase angles over the 90-minute simulation ranged over a full 360 degrees. The mean phase angle for the 9 m/s average wind speed case was approximately 67.7 degrees with a standard deviation of 77.2 degrees. For each mean wind speed, the turbulence intensity was selected to coincide with the value from the standard IEC class IA wind site [6]. The phase angle distributions roughly followed a Gaussian distribution.

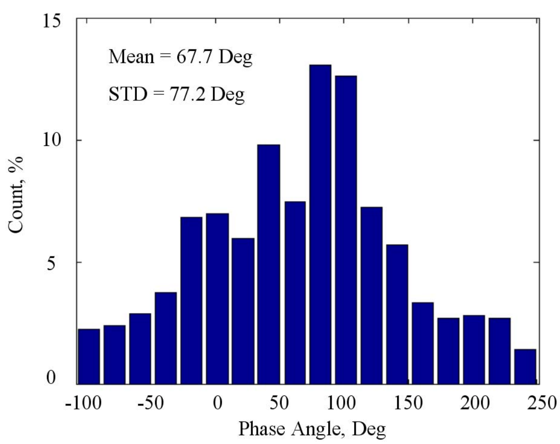

Figure 3: Phase Angles Distribution for 9 m/s Mean Wind Speed - 1.5 MW Turbine - IEC Class Ia Site

The mean and standard deviation of the phase angle distributions varied as a function of the average wind speed. As shown by Figure 4, the mean phase angle increased from 67.7 degrees at 9 m/s to approximately 87 degrees near cut-out.

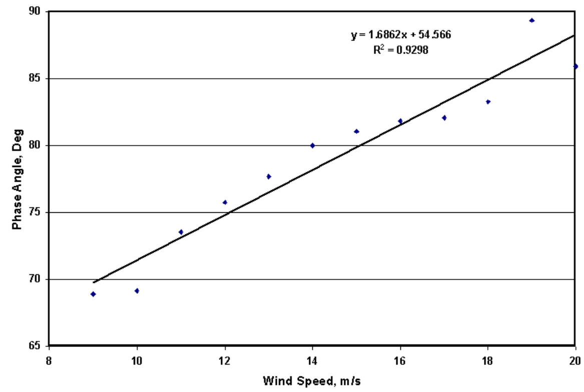

Figure 4: Mean Phase Angle as a Function of Average Wind Speed

The relationship between the mean phase angle and the average wind speed was approximated by a linear function. Although not shown here, the relationship between the standard deviation and average wind speed was also approximated by a linear function. However, the standard deviation of the phase angle actually decreases as wind speeds increase. This decrease coincides with a decrease in the turbulence intensity factor specified by the IEC standard for class Ia wind site wind conditions.

The linear approximations for the mean and standard deviation of the phase angle distributions were weighted by the standard IEC class IA wind speed Rayleigh probability distribution to create a 3-D phase angle probability density function, as shown in Figure 5.

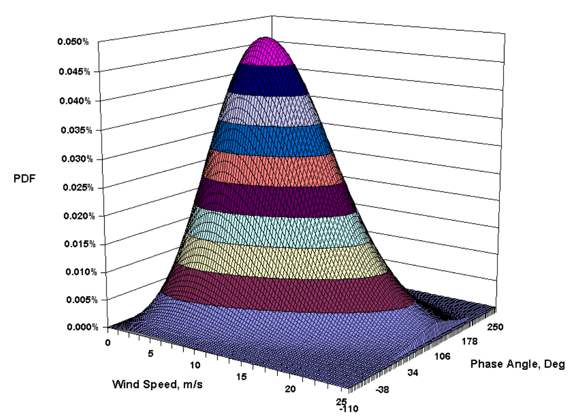

Figure 5: PDF for Phase Angle and Wind Speed for Generic 1.5 MW Blade

The 3-D distribution was integrated with respect to wind speed to create a two-dimensional aggregate probability density function that is independent of wind speed and a good approximation of how phase angle will vary under actual operating conditions. This provides a simplification of the blade's phase angle distribution that is necessary for implementation in full-scale laboratory testing. As shown in Figure 6, the aggregate probability function is approximately Gaussian. The mean phase angle for this distribution is 72 degrees. The standard deviation is approximately 55 degrees. Note that the mean phase angle is relatively low because the Rayleigh wind speed distribution heavily weights the lower wind speeds, which have lower mean phase angles than the higher wind speeds.

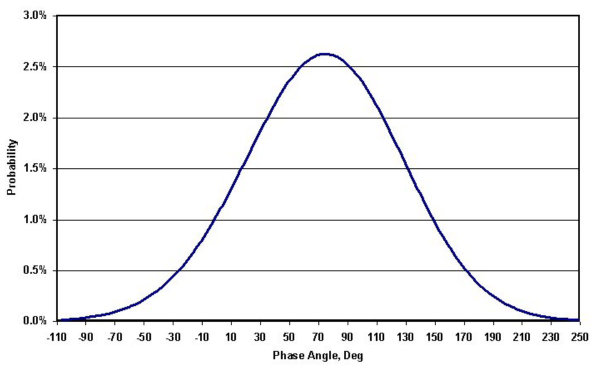

Figure 6: Aggregate Phase Angle Probability Density Function for Generic 1.5 MW Blade

From this analysis, it is apparent that a constant phase angle does not represent the actual loading experienced by wind turbine blades during operation. In order to evaluate the effect that variable phase angle testing may have on the cumulative fatigue damage, the aggregate phase angle distribution was used to construct a phase angle time history that could be applied using standard fatigue test equipment. Figure 7 shows a phase angle time history that has the same histogram as the aggregate probability density function. The time history was created by dwelling on a phase angle for the number of cycles prescribed by the aggregate distribution. In a blade test, the phase angle would be changed by adjusting the phase between the flap and lead-lag components in discrete steps that approximate the Figure 7 time series. In this example, the time history has a duration of 3 million load cycles, which would be typical for a blade test. Similarly, shorter time histories that match the aggregate distribution could be constructed and applied to the blade in a repetitive sequence to achieve the same total number of cycles. The effect of this type of sequencing was examined and will be described later.

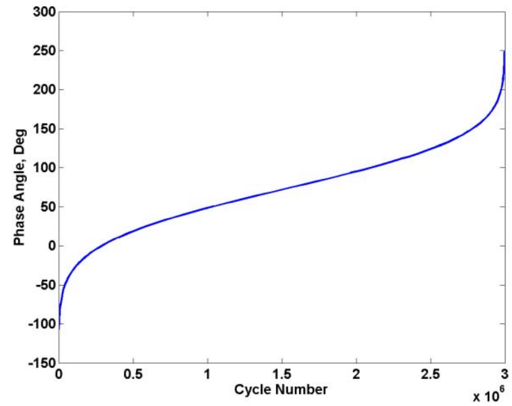

Figure 7: Phase Angle Time History for Generic 1.5-MW Blade

BLADE MODEL DESCRIPTION

With a variable phase angle time history now determined, it is possible to compare the effect that varying the phase angle during testing could have on the fatigue accumulation. To perform this analysis, a 3-D finite element model of a 1.5 MW blade originally created as part of the WindPACT research program was used [4]. The WindPACT blade FEM was modified for this project to model a typical test set-up used at NREL. The loading was applied at a single station located 24-meters from the root. Flap and lead-lag loads were applied using global rotor coordinates. The magnitude of the loading was selected by NREL to be representative of actual two-axis blade tests performed on a 1.5-MW blade.

Three blade cross-sections were selected for detailed analysis. These sections were taken at the root plane, the max chord station (6.3 meters), and at 15.75 meters (location of ply drop). For each of the cross-sections analyzed, the nodes numbers were defined as shown in Figure 8. The first node is located on the trailing edge and the number increases clockwise around the skin. The internal spar node number increase from bottom to top then left to right. The material property of the blade varies depending on which node is being considered.

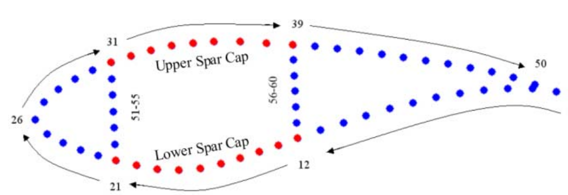

Figure 8: FEM Node Definition

Two classifications of material properties were used and will be considered in more detail in the next section.

DAMAGE MODEL DESCRIPTION

The accumulated damage was modeled using Miner's rule [1]. Although other damage accumulation models exist, this model is generally accepted and well understood. This model does have some deficiencies such as: load level independence, load sequence independence and a lack of load interaction accountability [8], but this model can show the influence of using a variable phase angle time history compared to a constant phase angle time history on the cumulative fatigue damage for a full-scale blade fatigue test. Therefore, Miner's Rule is used for this part of the analysis and as mentioned, a different fatigue damage model will be used later to analyze the influence of phase angle sequences.

The fatigue properties of the fiberglass-laminated material at each node location are important for calculating the fatigue accumulation. The actual fatigue properties of a wind turbine blade may vary widely over a multiplicity of unique structural features that include shear webs, spar cap rovings, adhesive bonds, ply terminations, core materials, etc. For the purpose of this generic study, the blade fatigue properties were described by two material classifications that are shown in Figure 9.

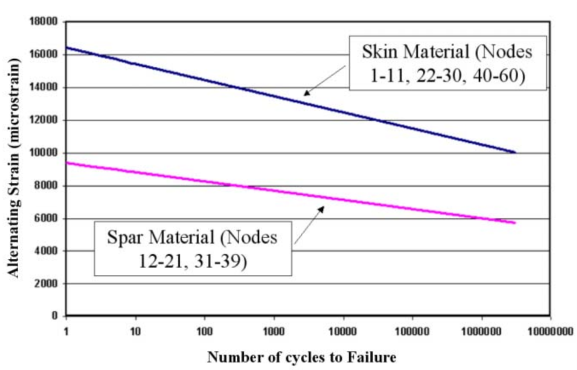

Figure 9: Strain-Cycle Properties for Fiberglass Spar Cap and Skin Material [8]

The dominant load carrying material is the unidirectional glass fibers along the spar, represented by the lower curve. All of the other laminates are characterized by the upper curve labeled "skin materials". This curve approximates materials that generally contain a higher content of biaxial fabric and a core material. This analysis is not intended to represent a fatigue life analysis for any particular blade, but any trends found here indicate a high potential for blades of similar construction to have the same sensitivities.

Prior to calculating damage, the axial strains resulting from the representative flap and lead-lag loads used in the WindPACT FEM were calculated for each phase angle. The simulated axial strains for each phase angle were distilled into a mean and alternating strain using a peak-valley detections algorithm. A Goodman diagram was used to extract the mean and calculate an alternating strain that would result in an equivalent amount of damage for each phase angle and node location.

RESULTS

Constant Phase Angles

Phase angle was first introduced at the NREL testing facilities during single axis testing, where the blade was pitched to a prescribed angle on the test stand to give a fixed resultant load, which could be decomposed into flap and lead lag components at a 0 degree phase angle. Dual-axis testing allowed the operating loads to be more accurately represented, and allowed the phase angle and load amplitude ratios to be specified to better match design conditions [10]. In all tests so far, the phase relationship between the flap and lead-lag loads has been defined as part of the fatigue load formulation and has been fixed at a constant value. As mentioned, for a single axis test, this value is always zero. For dual axis testing the value is usually between 70 and 90 degrees.

Constant phase angle experiments conducted earlier at NREL on two identical blades demonstrated that cracks appeared in one tenth the number of fatigue test cycles for a phase angle of zero degrees (single axis) compared to a test run with the same DELs but at a phase angle of 90 degrees [2]. The following results may help to provide an analytical basis to support these empirical results.

Since fatigue damage is a direct result of the strain encountered over the blade section, the relationship between phase angle and blade strains was first examined. As shown in Figure 10, changing the phase angle between the flap and lead-lag forces influences the equivalent alternating strain at a particular node. It can also be seen that nodal locations around the blade are dependent on the load phase angle, and that the character of this relationship is complex.

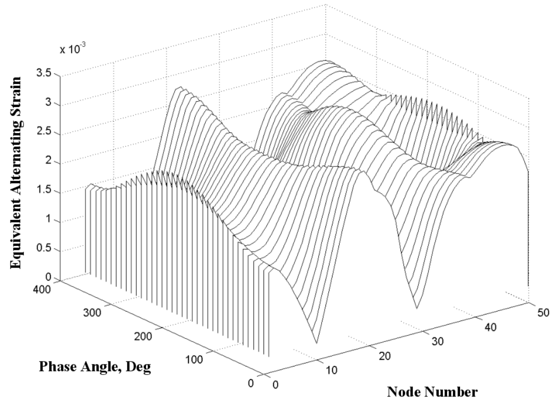

Figure 10: Effect of Load Phase Angle on Equivalent Alternating Strain (15.75 m)

Using Miner's rule and the strain-cycle curve for the blade material, the damage for each node location resulting from each phase angle was calculated. This result is illustrated in Figure 11 for the 15.75-m station based for a three million-cycle fatigue test.

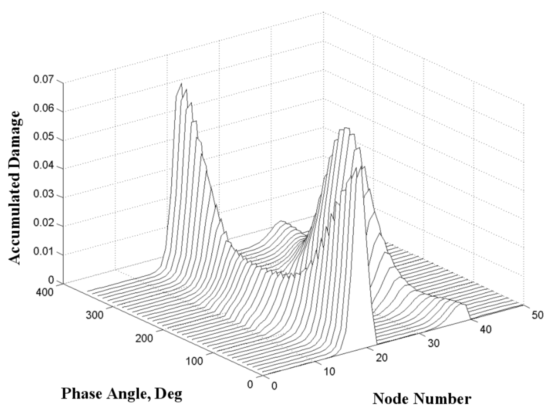

Figure 11: Effect of Load Phase Angle on Damage Accumulation (15.75 m)

Note that damage = 1.0 at failure. As shown, the fatigue damage is highly influenced by the selection of phase angle. Although the maximum damage for the assumed loading at this blade station is not near failure, the more significant effect is observed in how the damage is distributed around the blade profile.

Figure 12 shows the results for three typical phase angles used in testing: 0 degrees, 72 degrees and 90 degrees. This analysis agrees with the empirical results that a zero degree phase angle could cause failure much sooner than a 90-degree phase angle. This analysis shows that the nodal damage due to a constant phase angle fatigue test is dependent on the phase angle used.

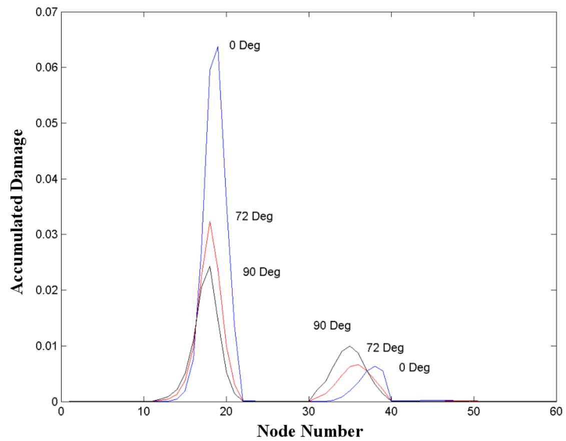

Figure 12: Accumulated Damage for Three Different Load Phase Angles (15.75 m)

Constant Versus Variable Phase Angle

The effect that different constant phase angles could have on fatigue testing is significant, however, analysis of the operating loads indicates that the operating conditions are not constant. As such, the damage accumulation predicted for a constant 72-degree phase angle fatigue test have been compared to the results for the Gaussian aggregate distribution shown in Figure 6.

As shown in Figure 13, the Gaussian aggregate phase angle distribution results in significantly higher damage at some locations around the blade than the constant phase angle distribution. This analysis suggests that the constant phase angle test may not produce a conservative test for every location around the blade profile.

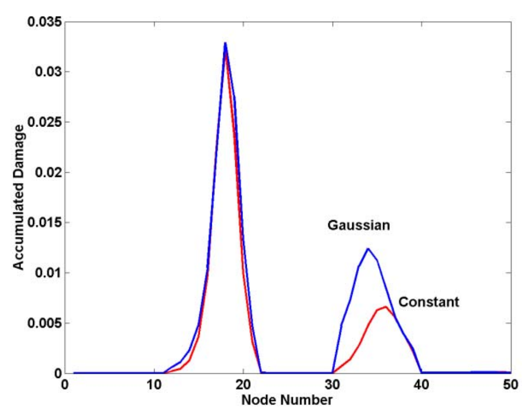

Figure 13: Variable Phase Angles (15.75m)

Influence of Defects

The previous analysis showed higher damage resulting from varying phase angle according to the derived aggregate distribution for a blade that is assumed to be built flawlessly, as the designer intended. However, one of the purposes of performing fatigue tests on actual full-scale samples is to empirically unmask defects in the structure that may have been introduced during production or design. The fatigue properties in a local area can be significantly affected by the presence of a material defect. To evaluate the effect of defects with respect to phase angle, defects were artificially added to the blade model at arbitrary locations. Stress concentrations for typical material defects in typical fiberglass blade laminates were assessed by Montana State University and were found to range from 1.2 to 2.5 [11]. To simulate the effects of a material defect, a strain concentration of 2.0, representing a moderate to severe defect, was applied to several nodes around the blade surface as shown in Figure 14.

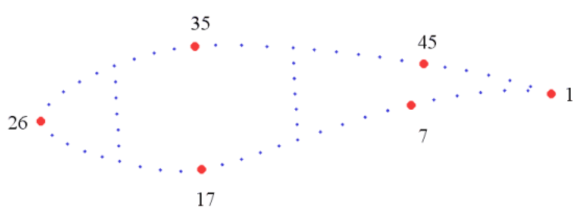

Figure 14: Material Defect Locations

Figure 15 shows the influence of a material defect located at node 45 on the accumulated damage. The results for a constant 72-degree phase angle fatigue test are compared to a variable phase angle fatigue test. It can be seen that the accumulated damage at the defect is dependent on the phase angle.

The normalized damage occurring from the variable phase angle fatigue test with respect to the constant phase angle fatigue test is shown in Figure 16 for the six defect locations. In each case, the damage from the constant phase angle test was fixed at 1.0. From this figure, it can be seen that in four of the six locations the variable phase angle fatigue test has a much higher probability of detecting defects. For the example used in Figure 15, node 45 would generate approximately three times more damage under variable phase loading than at a constant phase angle of 72 degrees. At node 35, this difference was calculated to 12 times more damage for the variable phase angle case.

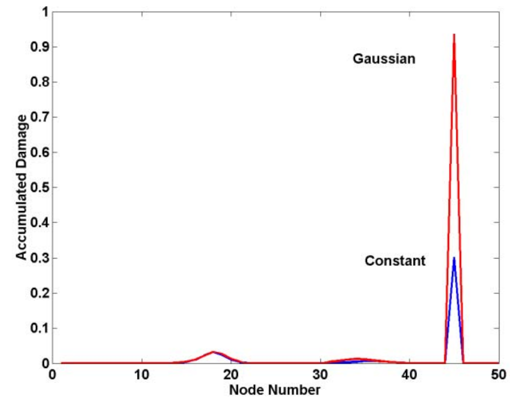

Figure 15: Comparison of Damage Accumulation Defect at Node 45 (15.75m) – Variable Phase Angle versus Constant Phase Angle

In two locations, on the lower spar cap (node 17) and the leading edge (node 26), there was not a significant difference between the methods for the specific loading used.

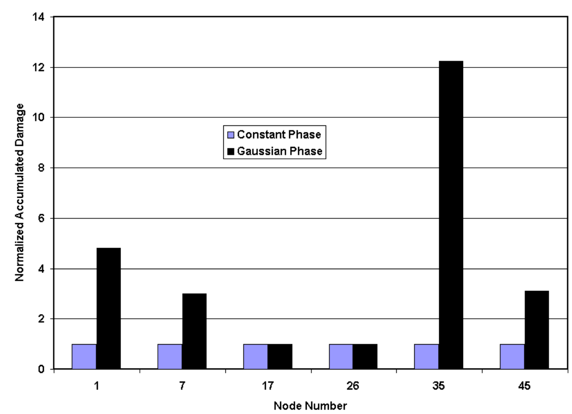

Figure 16: Normalized Accumulated Damage for Fatigue Tests with Variable Phase Angles to Constant 72-Degree Phase Angle

This analysis indicates that a variable phase angle fatigue test, besides being more representative of operating conditions, could find defects that a constant phase angle fatigue test would not. While some empirical data exists to support the results for the constant phase angle test case, there are no experimental evaluations of a variable phase angle fatigue test. Based on this analysis, it would be worthwhile to explore variable phase angle testing on a full-scale blade test.

Effect Of Phase Angle Sequencing

With variable phase angle tests, it is possible to apply the phase angles in different orders but still have the same overall resulting distribution. Research has found that the order in which loads are applied to a composite material may have an influence on the amount of damage that is accumulated [12-14]. In this analysis, it has been observed that variable phase angle fatigue testing can influence the distribution of damage around the blade profile. The question remaining is: how does the length of the phase angle time history influence the magnitude and distribution of the damage around the blade profile? To determine the answer to this question, it was necessary to use a nonlinear damage accumulation model. Since it was not desirable to limit this analysis to a specific type of failure mode, the Marco-Starkey damage accumulation model shown by Equation 1 was used [5].

Eq. 1) $$D = \sum_i \left(\frac{n_i}{N_i} \right)^V$$

Where,

D = Accumulated Damage
n = # of Applied Cycles
N = # of Cycles to Failure
i = Load Case Index
v = tuning parameter

The tuning parameter, v, was determined using the MSU/DOE Fatigue Database [12]. The results of this analysis are highly influenced by the value selected for v. Based on the results of the coupon tests, the parameter v could realistically be any value between 0.265 and 1.0 (Miner's rule). Although the value of 0.265 resulted in a better correlation to the coupon fatigue information than the value of 1.0, an intermediate value of 0.74 was selected for this analysis.

As shown in Figure 17, the number of phase angle sequence repetitions was increased to compare the amount of damage that would be accumulated during a fatigue test.

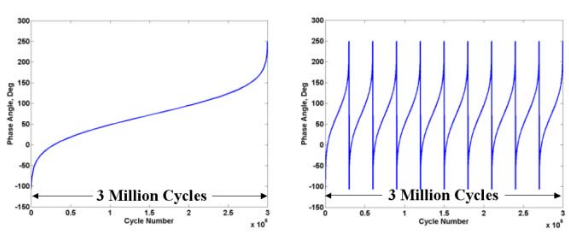

Figure 17: Comparison of One Phase Angle Sequence to Ten Phase Angle Sequences

In each case, the number of cycles contained in each sequence was reduced so that the total number of applied test cycles and the overall phase angle distribution was the same as the Gaussian aggregate. As shown by Figure 18, for the same number of total cycles, the more often the phase angle sequence is repeated, the more damage is accumulated. This trend is present for any value of v that is less than 1.0, with v = 1.0 corresponding to Miner's Rule, which would predict no influence due to sequence. The Marco-Starkey damage accumulation model indicates that this effect is significant and should not be ignored.

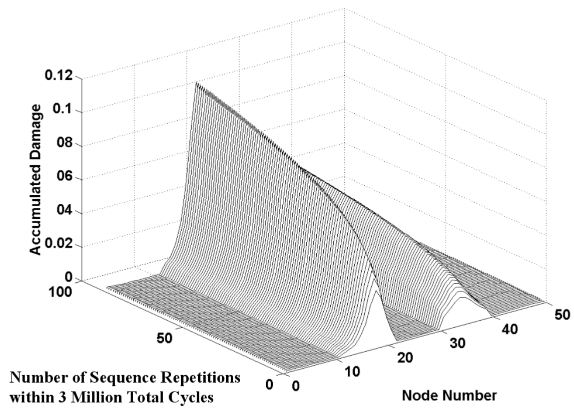

Figure 18: Effect of the Number of Sequence Repetitions on Damage Accumulation

This analysis indicates that the number of times a sequence is repeated is a significant factor in determining the total amount of damage accumulation for a variable phase angle fatigue test. The number of sequence repetitions did not affect the proportions of the damage distribution around the blade profile, as long as the overall phase angle distribution remained the same.

CONCLUSIONS

This paper examined the importance of load phase angle variations with respect to fatigue damage. The operating loads on a conventional three bladed up-wind 1.5-MW wind turbine blade were analyzed over a range of operating conditions, and a two-dimensional aggregate probability distribution for the phase angles between the in-plane (lead-lag) and out-of-plane (flap) loads was determined for the generic 1.5 MW wind turbine. The fatigue damage resulting from this variable phase angle was compared to the damage using a constant phase angle using finite element analysis. Sequence effects of various phase angle progressions were also considered using a nonlinear damage accumulation model.

Results show the following:

- Phase angle between flap and lead-lag loading varies widely during turbine operation and can be represented by a Gaussian distribution.
- Constant phase angle simplifications used for blade testing and fatigue analysis are non-conservative with respect to damage accumulation.
- Constant phase angle approximations may conceal blade defects that are introduced by design, manufacturing or material deficiencies.
- Even if phase angle is properly accounted for using linear damage principles, non-linear damage models show that the sequencing strategy for introducing phase angle into a validation test can influence damage accumulation.
- Variable phase angle can be introduced into blade test loading without major system modifications.
- Variable phase angle should be accounted for during wind turbine blade testing and blade fatigue analysis if possible.

ACKNOWLEDGEMENTS

The authors would like to thank the other contributors who have made this project possible. Dayton Griffin and Don Roberts of Global Energy Concepts were instrumental in developing the finite element blade model and running the load cases used in this analysis. Pat Moriarty's WindPACT blade model provided the tool to do the loads and phase angle analysis. The U.S. Department of Energy is greatly acknowledged for its support of this project and its continuing support of structural testing.

REFERENCES

1. Miner, A., "Cumulative Damage in Fatigue," *Transactions of the ASME*, Vol. 67, 1945.
2. Larwood, S., Musial, W., Freebury, G., Beattie, A., "NedWind 25 Blade Testing at NREL for the European Standards Measurement and Testing Program," NREL/TP-500-29103, March 2001.
3. Wilson, R.E., Freeman, L.N., Walker, S.N., Harman, C.R., *Users' Manual for the FAST_AD Advanced Dynamics Code*, OSU/NREL Report 95-01, September 1995.
4. Griffin, D. A. (2001). WindPACT Turbine Design Scaling Studies Technical Area 1 -- Composite Blades for 80- to 120-Meter Rotor; 21 March 2000 - 15 March 2001. 44 pp.; NICH Report No. SR-500-29492.
5. Marco, S., Starkey, W., "A Concept of Fatigue Damage," *Transactions of the ASME*, 76(1), 1954.
6. IEC 1999-02. *IEC 61400-1: Wind Turbine Generator Systems*. 1999.
7. Hartin, J.R., "Evaluation of Prediction Methodology for Blade Loads on a Horizontal Axis Wind Turbine," 9th ASME Wind Energy Symposium, 1990, New Orleans, Louisiana, January 14-18, 1990.
8. Van Paepegem, W., Degrieck, J., (2002) "Effects of Load Sequence and Block Loading on the Fatigue Response of Fibre-reinforced Componsites," *Mechanics of Advanced Materials and Structures*, 9(1).
9. Van Grol, H., Bulder, B., *Reference Procedure to Establish Fatigue Stresses for Large Size Wind Turbines: A State of the Art Report, Volume I: Main Body of the Report and Annexes*, Netherlands Energy Research Foundation ECN, the Netherlands, 1994.
10. Hughes, S.D., Musial, W.D., and Stensland, T., "Implementation of a Two-axis Servo-hydraulic System for Full-scale fatigue Testing of Wind turbine Blades", NREL/CP-500-26896, August 1999.
11. Mandell, J., Samborsky, D., Scott, M., Cairns, D., "Effects of Structural Details on Delamination and Fatigue Life of Fiberglass Laminates," AIAA-98-0061.
12. Wahl, N., Samborsky, D., Mandell, J., Cairns, D., "Spectrum Fatigue Lifetime and Residual Strength for Fiberglass Laminates," AIAA-2001-0025.
13. Schaff, J., Davidson, B., "Life Prediction Methodology for Composite Structures. Part I – Constant Amplitude and Two Stress Level Fatigue," *Journal of Composite Materials,* Vol. 31, No. 2., 1997.
14. Schaff, J., Davidson, B., "Life Prediction Methodology for Composite Structures. Part II – Spectrum Fatigue," *Journal of Composite Materials*, Vol. 31, No. 2., 1997.

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 2003	Conference Paper

4. TITLE AND SUBTITLE
The Effect of Load Phase Angle on Wind Turbine Blade Fatigue Damage

5. FUNDING NUMBERS
WER3.1505

6. AUTHOR(S)
D.L. White and W.D. Musial

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-500-34837

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This paper examines the importance of phase angle variations with respect to fatigue damage. The operating loads on a generic conventional three-bladed upwind 1.5-MW wind turbine blade were analyzed over a range of operating conditions, and an aggregate probability distribution for the actual phase angles between the in-plane (lead-lag) and out-of-plane (flap) loads was determined. Using a finite element model of a generic blade and Miner's Rule, the accumulated theoretical damage (based on axial strains) resulting from a fatigue test with variable phase angles was compared to the damage resulting from a fatigue test with a constant phase angle. The nodal damage distribution at specific blade cross-sections are compared for the constant and variable phase angle cases.
The sequence effects of various phase angle progressions were also considered. For this analysis, the finite element results were processed using the nonlinear Marco-Starkey damage accumulation model. Each phase angle sequence was constrained to have the same overall phase angle distribution and the same total number of cycles but the order in which the phase angles were applied was varied.

14. SUBJECT TERMS
wind energy; wind turbine; fatigue; load phase angle

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102